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WOOD AND OTHER RENEWABLE RESOURCES

Quantifying greenhouse gases from the production, transportation and utilization of charcoal in developing countries: a case study of Kampala, Uganda

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Abstract

Purpose This study aims to quantify greenhouse gases (GHGs) from the production, transportation and utilization of charcoal and to assess the possibilities of decreasing greenhouse gases (GHGs) from the charcoal industry in general in Uganda. It also aims to assess the emission intensity of the Ugandan "charcoal production" sector compared to that of some other major charcoal producing nations.

Methods This work was done in accordance with ISO 14040 methodology for life-cycle assessment (LCA), using GABi 4.0—a software for life-cycle assessment. A cradle-to-grave study was conducted, excluding emissions arising from machinery use during biomass cultivation and harvesting. The distance from charcoal production locations to Kampala was estimated using ArcGIS 10.0 software and a GPS tool. Emission data from a modern charcoal production process (PYREG methane-free charcoal production equipment), which complies with the German air quality standards (TA-Luft), was compared with emissions from a traditional charcoal production process. Four coupled scenarios were modelled to account for differences in the quantity of greenhouse gases emitted from the "traditional charcoal production phase", "improved charcoal production phase (biomass feedstock sourced sustainably and unsustainably)", "transportation phase" and "utilization phase". Data for this study was obtained via literature review and onsite measurements.

Results and discussion The results showed that greenhouse gases emitted due to charcoal supply and use of traditional production technique in Kampala was 1,554,699 tCO_2eq, with the transportation phase accounting for approximately 0.15 % of total greenhouse gases emitted. The utilization phase (charcoal cookstoves) emitted 723,985 tCO_2eq (46.6 %), while the charcoal production phase emitted 828,316 tCO_2eq (53.3 %). Changing the charcoal production technology from a traditional method to an improved production method (PYREG charcoal process) resulted in greenhouse gases reductions for the city of 230,747 tCO_2eq; however, by using sustainably sourced biomass, this resulted in reductions of 801,817 tCO_2eq.

Conclusions This study showcased and quantified possible GHG emission reduction scenarios for the charcoal industry in Uganda. The result of 3 tCO_2eq emitted per tonne of charcoal produced, using earth mound method, can be applied to other countries in Eastern Africa where similar charcoal production methods are used; this will allow for somewhat better regional estimates of the inventory of greenhouse gas emissions from the production of charcoal.

The results of this study also suggests that the primary use of charcoal for cooking will lead to increases in GHG emissions and increases in deforestation on the long term, if legal frameworks are not made to ensure that biomass used for charcoal production is obtained via sustainable sources or if alternative cheap energy-generating technologies for cooking are not developed and deployed to the masses.

Keywords Charcoal production · Earth mound kiln · Greenhouse gases · Life-cycle assessment · Methane-free charcoal equipment

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1 Introduction

1.1 Background

Uganda is a land-locked country situated in East-Central Africa with an area covering 241,038 km^2, with an estimated population of 34 million in 2012 and a population growth rate of 3.58 per annum, which is the fourth fastest in the world (Central Intelligence Agency 2012). The Ugandan economy has been experiencing high growth rates in the last decade, with 7.2 %, 5.2 % and 6.4 % real growth rates for the years 2009, 2010 and 2012, respectively (Central Intelligence Agency 2012). A growing population combined with a growing economy leads to higher energy demand.

Biomass accounts for more than one half of national energy and as much as 95 % of domestic energy in some developing countries (Reddy 1996). In Uganda, it even contributes over 90 % of the total energy consumed and provides almost all the energy used to meet basic energy needs for cooking and water heating in rural areas, most urban households, institutions and commercial buildings. Biomass is the main source of energy for rural industries. Limited availability of electricity and high prices of petroleum products, constitute barriers to a reduction in the demand for biomass. Trading in biomass especially charcoal contributes to the rural economy, in terms of rural incomes, tax revenue and employment. Fuelwood requirements have contributed to the degradation of forests as wood reserves are depleted at a rapid rate in many regions (MEMD 2007).

In Uganda, like in any other country, the energy sector plays a central role in the economy. Energy is the engine for economic growth and development and a vital input into all the productive and social sectors of the economy. Energy is sourced basically from firewood, charcoal, petroleum products and electricity, with contributions of 88 %, 5 %, 6 % and 1 %, respectively (Kisakye 2004). Considering that electrification access in Uganda is still very low, at approximately 9 % nationally and 3 % in rural areas (MEMD 2007), this has lead to a steadily increasing demand for biomass for energy generation.

Kampala is the capital of Uganda and also the largest urban settlement in the country. Data from the last national census conducted in 2002 shows that the total urban population in the county was approximately three million (12.4 % of the country population), and Kampala had a population of 1.2 million (40 % of the entire urban population in the country); the second most populous city is Lira, with a population of 120,000 (Ugandan Bureau of Statistics 2006).

The Food and Agriculture Organization of the United Nations report about 46 million and 47 million tonnes (Mt) of wood charcoal were produced worldwide in 2005 and 2010, respectively. Africa produced about 24 million tonnes (Mt) and 28 million tonnes (Mt), while East-Africa produced nine million tonnes (Mt) and 11 million tonnes (Mt), in 2005 and 2010, respectively (FAO 2012). This implies that East-Africa accounted for about 20 % and 23 % of the global production of wood charcoal for 2005 and 2010, respectively.

The consumption of charcoal in Uganda has a distinctive pattern, with its consumption mainly in urban settlements, while the urban poor and rural dwellers consume mainly fuelwood. A study conducted by the Ugandan Ministry of Energy and Mineral Development showed that charcoal consumption increases at a rate close to the urban growth rate of 6 % per annum, clearly establishing the pattern of urban consumption (MEMD 2007). With mounting urbanization, the Ugandan populace is increasingly shifting from fuelwood to charcoal for domestic cooking and heating (Girard 2002).

1.2 Objective

The objective of this study is the assessment of GHG from the production, transportation and utilization of charcoal in Kampala, Uganda. A cradle-to-grave study was conducted, excluding emissions arising from machinery use during biomass cultivation and harvesting.

No study has been conducted to quantify the emissions that results from the operations of the charcoal industry—production, supply and consumption—for Kampala City and the entire country at large. Greenhouse gas (GHG) emissions from charcoal result from three distinct processes: land-use change (LUC) processes induced by wood harvest; pyrolysis of woody feedstock and combustion of charcoal. This study includes emissions resulting from the transportation of finished charcoal. It is important to distinguish this type of emission study from health-focused assessments. Air pollution studies evaluate the concentrations of particulate matter, carbon monoxide or other pollutants in a room or where people are exposed and pollutants in the outdoor environment. Emission studies assess the quantity or rate of pollutants emitted from a process. It is also important to understand the terms, sustainably and unsustainably obtained biomass:

Biomass feedstock is said to have been obtained sustainably, thus defined as renewable, if,

(1) the land remains a forest;
(2) sustainable management practices are in place to ensure that the level of carbon stocks does not systematically decrease over time (stocks may temporarily decrease due to harvesting); and
(3) all national or regional forestry and nature conservation regulations are complied with. Biomass that fails to meet all three conditions is "non-renewable biomass" (NRB) by default, thus unsustainably obtained (CDM-EB 2006).

Under optimal conditions, biomass combustion results almost entirely in the emission of water vapour and carbon dioxide (CO_2). Water vapour, the most prevalent GHG in the

atmosphere, is quickly incorporated in the hydrologic cycle with no measurable warming effect, and CO_2, the most common anthropogenic GHG, can be absorbed by new plant growth through photosynthesis. Therefore, if biomass is harvested in a sustainable way so that its long-term stocks are not depleted and burned under ideal combustion conditions, it is effectively GHG neutral (Bailis et al. 2003).

The production, transportation and utilization of charcoal constitute a critical energy and economic cycle in the economy of the country. Intertwined in "charcoal production" are its global warming effects because much of the feedstock used for production are sourced from unsustainably managed plantations, leading to net carbon dioxide emissions. In addition, the pyrolysis of biomass also produces products of incomplete combustion (PICs), such as methane and non-methane volatile organic substances (NMVOCs), which have a higher GWP than carbon dioxide. The "transportation phase" also contributes to global warming by greenhouse gases emitted from the combustion of fuel in diesel/gasoline powered trucks. The "utilization phase" (cookstove) emits greenhouse gases when charcoal is burnt for energy, also, products of incomplete combustion (PICs) emitted when charcoal is burnt constitute a major source of in-door air pollution, with its negative multiplier effects on human health.

1.3 Procedure

To quantify the emissions, the ISO 14040 methodology for life-cycle assessments (LCA) has been applied. The sections 1, 2, 3 and 3.4 of this work represent the "Goal and scope definition", "Inventory analysis", "Impact assessment" and "Interpretation", respectively, according to the ISO 14040 methodology for LCAs. Four scenarios were modelled. Scenarios 1–3 and 4 assessed GHG-related emissions for Kampala city and the entire country, Uganda, respectively.

i. Scenario 1: The first scenario will quantify emissions from an "Earth mound charcoal production process" coupled to emissions from transportation phase and coupled to "utilization phase (charcoal burning)" of charcoal. For this scenario, its assumed biomass feedstock is obtained unsustainably. The summation of emissions from the three phases represents total emissions for scenario 1.
ii. Scenario 2: The second scenario will quantify emissions from a "methane-free pyrolysis charcoal plant" coupled to emissions from the transportation phase and coupled to emissions from the utilization phase (charcoal burning). For the second scenario, it was assumed that the biomass feedstock is obtained unsustainably. The methane-free charcoal equipment used in the entire study is called "PYREG process equipment" manufactured by PYREG GmbH, a German equipment manufacturer. The equipment complies with the German technical instructions on air quality control—TA Luft, which is amongst the strictest in the world.
iii. Scenario 3: The third scenario will quantify emissions from a methane-free pyrolysis charcoal plant coupled to the emissions from the transportation phase and the emissions from utilization phase (charcoal burning). For the third scenario, it was assumed that the biomass feedstock is obtained from a sustainably managed plantation, thus biogenic CO_2 emission is excluded from inventory. This scenario will assess GHG-related emissions for the city of Kampala alone.
iv. Scenario 4: The fourth scenario will quantify emissions from an Earth mound charcoal production process coupled to emissions from the utilization phase (charcoal burning) and assume the biomass feedstock is obtained unsustainably.

The result from the first scenario modelled would provide an estimate of the total greenhouse gases emitted due to demand of charcoal in Kampala. By decoupling the model, the utilization phase provides estimates of emissions from charcoal cookstoves in Kampala alone. These results would be useful when compiling a national greenhouse gas (GHG) inventory. By comparing total emissions in scenario 1 and scenario 2, the result would provide an estimate of possible GHG emission reductions from changes in charcoal production technology. Also, by comparing total emissions from scenario 1 and scenario 3, the results would provide an estimate of possible emission reductions from changes in charcoal production technology and changes when biomass feedstock is sourced sustainably. The result from the fourth scenario would provide an estimate of emissions from charcoal production and utilization for the entire country.

2 Materials and methods

2.1 Materials

Hardware's used: a personal computer and a handheld GPS.

2.2 Data sources

The sources of data are grouped into the three unit operations that make up the life cycle of charcoal, namely, production, transportation and utilization.

1) Production data

   a) Improved charcoal production:

- Quantitative data on input-output flows (amount of biomass required and corresponding amount of charcoal

produced) of PYREG charcoal production plant were obtained from the manufacturer, PYREG GmbH, Trinkbornstrasse 15–17, 56281, Dörth, Germany.

- Non-CO_2 emissions were derived using the German Technical instructions on Air Quality Control—TA Luft, section 5.2.
- Carbon dioxide emissions were derived using the IPCC 2006 Guidelines for National Greenhouse Gases Inventory, volume 5, Waste, Chapters 2 and 5.
- Emission factors from electricity generation were obtained from the US Department of Energy, Energy Information Administration.

b) Earth mound charcoal production:

- Data was obtained from a study conducted by Pennise et al 2001, “Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil”.

2) Transportation data and data on amount of charcoal consumed in Kampala

    - GPS coordinates of Owino market, charcoal section, Kampala, were obtained with a handheld GPS device, on site.
    - Data on supply of charcoal to Kampala in 2004, showing quantitative amounts of charcoal coming from different districts in the country to Kampala, was obtained from a German Society for International Cooperation (GIZ)-sponsored project in 2004, titled “A study on charcoal supply in Kampala”.
    - Administrative and road vector data, used to estimate the total distance travelled, was obtained from “AFRICOVER” an FAO multipurpose database on environmental resources.

3) Data on emission factors from charcoal burning

    - Data was obtained from literature “Emission factors for open and domestic biomass burning for use in atmospheric models” (Akagi et al. 2011).

4) Amount of charcoal produced in Uganda from 1965 to 2011 was obtained from FAOSTAT.

2.3 Methods

The system boundaries of the work covered the production of charcoal, the transportation of charcoal and its utilization.

A functional unit of 1 kg of charcoal was the basis of the analysis; this was chosen for easy comparability with previous related studies in literature and comparability of different scenarios modelled in this study.

GaBi 4.0 software was used to calculate the total amount of greenhouse gases for the charcoal production and utilization phase, using the CML December 7, 2001, global warming potential impact assessment characterization factors.

Figure 1 shows a flow diagram showing the procedure followed in this study:

Step 1 Preparing input-output inventory of unit processes of charcoal life cycle in GaBi 4.0 sustainability software.

Step 2 Excel-based assessment to derive Ugandan charcoal production data for the years 2010, 2015 and 2020.

The yearly charcoal production data for 1965–2011 was plotted against time (year), this gave an R^2 value of 99.5 %, on the basis of the high correlation between yearly production amount and time; trend analysis in Microsoft Excel 2007 was used to derive data for 2012–2023.

Step 3 A GIS-based assessment using the “Network Analyst” extension in ArcGIS 10.0 was used to estimate the total distance covered in the supply chain, from production locations to Kampala main charcoal market. Figure 2 shows a measured distance form one charcoal production location—Masindi—to Kampala.

Step 4 Transportation model

The World resource Institute GHG Protocol Excel-based tool for calculating greenhouse gases from mobile combustion sources was used (World Resource Institute 2012). IPCC default emission factors, characterization factors and estimate of total distance travelled from charcoal production sites to Kampala served as input data.

Step 5 Modelling of scenarios using the GaBi 4.0 software. The software was used to calculate charcoal production- and “charcoal utilization-” related GHG emissions of scenarios 1–4 stated in section 1.3.

(1) Scenarios 1–3: Computation was done based on a functional unit of 1 kg of charcoal produced and utilized; this was then extrapolated to—279,664 tonnes—the total amount of charcoal supplied to Kampala, for the year of study—2004.

(2) Scenario 4: This scenario assessed GHG emissions for the entire country. Computation was done based on a functional unit of 1 kg of charcoal produced and utilized; this was extrapolated to—792,417 tonnes—the total amount of charcoal produced in Uganda, for—2004—the year of study. Three additional sub-scenarios were modelled for the years 2011, 2015 and 2020 to

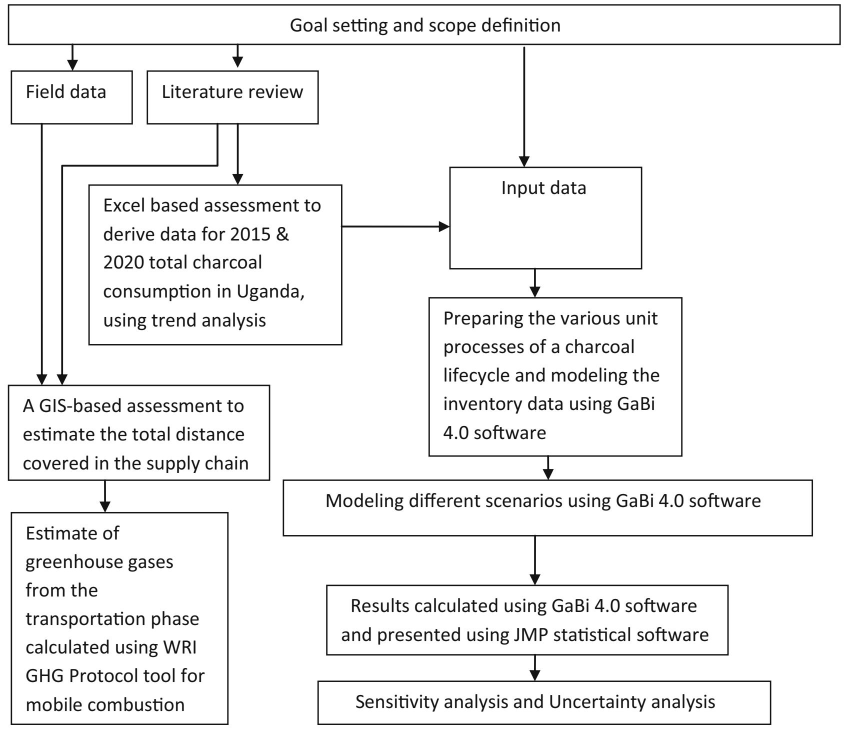

Fig. 1 Procedure flow diagram

calculate annual greenhouse gases in CO_2 equivalence emitted, respectively.

3 Results and discussion

3.1 Greenhouse gases from the transportation phase

Using the input data derived from the GIS-based analysis carried out, the World Resource Institute's (WRI) excel-based model for calculating greenhouse gases from mobile sources gave a result of 2,397.5 tCO_2eq.

3.2 Summary of results

Tables 1, 2, and 3 show the results of the four scenarios modelled including the transportation phase, using 2004 data; future projections of greenhouse gases emissions from charcoal and annual amount of biomass consumed and biomass consumption projections for charcoal production in Uganda, respectively. In Table 1, we observe that the results of scenarios 1–3 for the utilization phase and the "transportations phase" are the same for each respective scenario.

Figure 3 shows the results for the different "charcoal production phase" scenarios.

3.2.1 Issues related to the transportation phase

The distance computed from charcoal production locations to Kampala had some shortcomings. Charcoal is sold at different random temporary locations in small scale in the districts. To measure the distance from these locations, a centralized location for each district was computed using ArcGIS 10.0 software, thus, the resulting distance from districts to Kampala, which was used to compute the resulting greenhouse gases, was underestimated. However, when we consider that most trucks upon delivery of charcoal to Kampala return to production locations empty, that means computing for a two-way trip rather than a one-way trip would result in an increase in greenhouse gases from the transportation phase by a factor of 2.

3.3 Sensitivity and uncertainty analysis

3.3.1 Sensitivity analysis

Tables 4 and 5 show the results for sensitivity analysis conducted for scenario 1 and scenario 2, respectively. The results of the one-way sensitivity analysis (Tables 4 and 5) show that for each greenhouse gas (carbon dioxide, nitrous oxide and methane) which served as a parameterized input in the models, a change of 10 and 50 % in its value resulted in a maximum deviation of ±0.022 and ±0.11 %, respectively, for

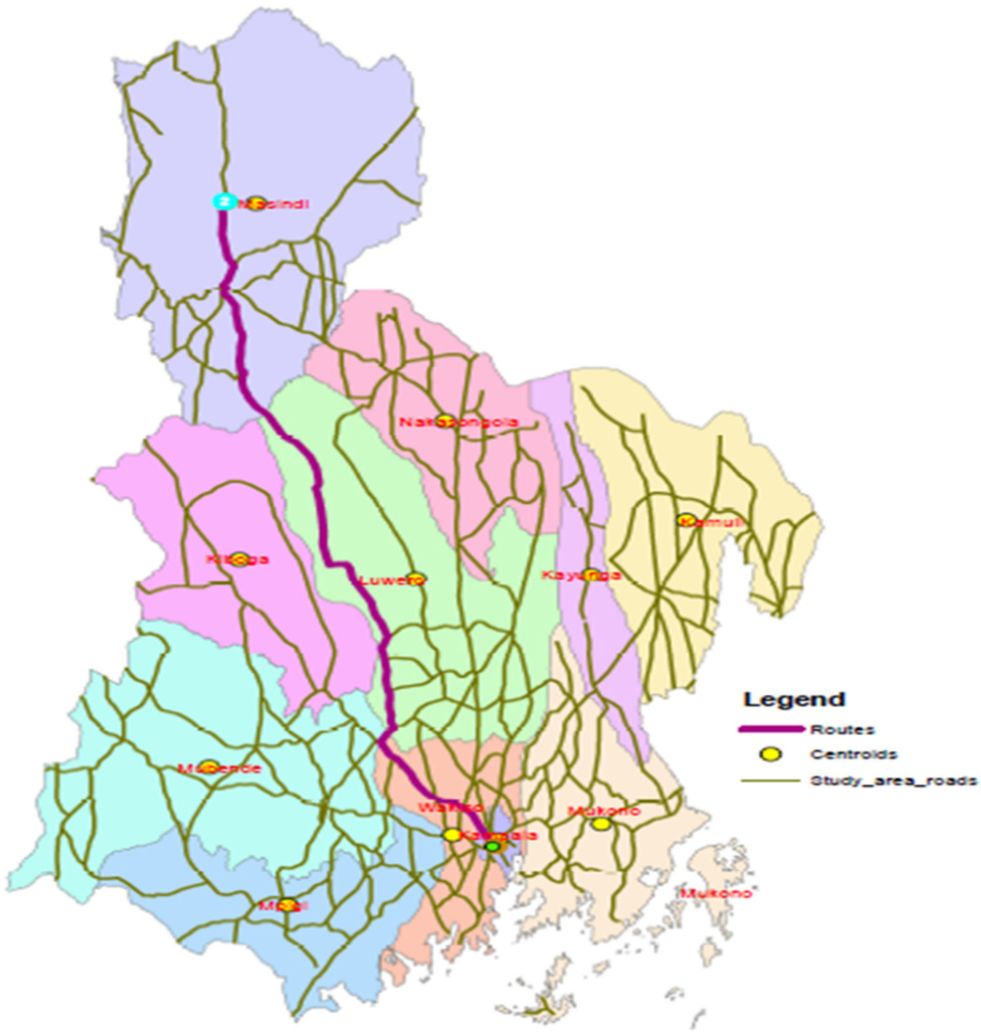

Fig. 2 A map showing a route from a centralized location in Masindi District to Owino market, Kampala

each model output. This shows that the input variables used in this study were stable.

3.3.2 Uncertainty analysis

Table 6 shows the result of an uncertainty analysis—Monte Carlo analysis—conducted for scenario 4. The uncertainties (minimum values, maximum values and standard deviation) were incorporated into the model to determine the possible range of results (stochastic mean and percentiles), which were then compared with the initial study result (scenario 4) obtained. Fifty thousand (50,000) iterations were performed, assuming a uniform distribution i.e. each random input variable had an equal chance of occurrence.

Table 1 Summary of scenario results (total greenhouse gases from charcoal production, transportation and utilization, using 2004 data)

Phase	Scenario 1 (tCO_2eq) for Kampala[a]	Scenario 2 (tCO_2eq) for Kampala[a]	Scenario 3 (tCO_2eq) for Kamapala[a]	Scenario 4 (tCO_2eq) for Uganda[b]
Charcoal production	828,316	597,569	26,498	2,347,002
Utilization	723,985	723,985	723,985	2,051,385
Transportation	2,397.5	2,397.5	2,397.5	Not calculated
Total	1,554,699	1,323,952	752,882	4,398,387

[a] Results for the city of Kampala based on the total mass produced, transported and utilized

[b] Results for the entire country—Uganda—based on the total mass produced and utilized

Table 2 Future projections of greenhouse gases emissions from charcoal production (earth mound production process) and utilization in Uganda

Year	tCO_2eq emitted[d]
2004[a]	4,398,387.58
2011[b]	5,173,918.44
2015 projection[c]	5,384,927.46
2020 projection[c]	5,830,158.39

[a] Calculated using FAO estimate of charcoal produced for 2004

[b] Calculated using FAO estimate of charcoal produced for 2011

[c] Calculated using FAO estimates of charcoal produced for 1965–2011 to derive input data for 2015 and 2020

[d] Results based on total mass of charcoal produced and utilized in Uganda.

To determine the reliability of the study results, an uncertainty analysis (Monte Carlo simulation) was conducted for scenario 4. Comparing the results of the 10th percentile, the 90th percentile and the study result (see Table 6), we observe all results of the simulation are of the same order of magnitude and the study result specifically falls in between the 10th and 90th percentile values. This confirms that the estimates gotten in this study are reliable, thus validating the study conducted. Parameters tested were literature-sourced carbon dioxide, nitrous oxide and methane data used in modelling scenario 4.

3.4 Discussion

3.4.1 Discussion of results

The result of scenario 1 showed emissions of 1,554,699 tCO_2eq. This value represents the total amount of greenhouses gases (GHGs) emitted due to demand of charcoal in Kampala. The utilization phase in this scenario gave a result of 723,985 tCO_2eq; this value represents an estimate of greenhouse gases emitted from charcoal cookstoves in Kampala. It is worthy to note that data used for the utilization phase, i.e. charcoal burning, represents emissions for both traditional and improved cookstoves.

Table 3 Annual amount of biomass consumed and biomass consumption projections for charcoal production in Uganda

Biomass consumed	Metric tonne[d] (t)
2004[a]	2,852,701
2011[b]	3,353,278
2015[c]	3,492,550
2020[c]	3,781,317

Charcoal production process and efficiency of biomass conversion to charcoal are based on a study conducted by Pennise et al. 2001, "Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil"

[a] Calculated using FAO estimate of charcoal produced for 2004

[b] Calculated using FAO estimate of charcoal produced for 2011

[c] Calculated using FAO estimates of charcoal produced for 1965–2011 to derive input data for 2015 and 2020

[d] Results based on total mass of charcoal produced and utilized in Uganda

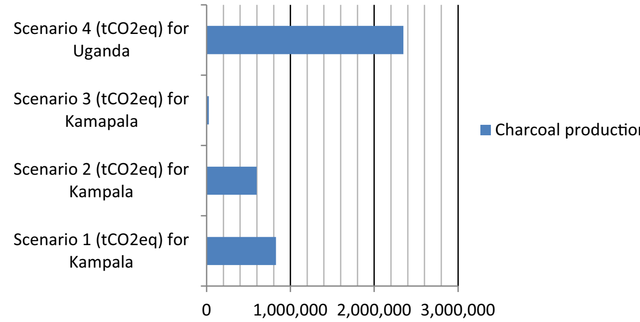

Fig. 3 Charcoal production scenarios

The result of scenario 2 had emissions of 1,323,952 tCO_2eq; this value represents the total amount of greenhouse gases emitted due to demand of charcoal in Kampala, when biomass is sourced unsustainably and charcoal is produced using improved production technologies. By decoupling the model and comparing only greenhouse gases from charcoal production phases for scenarios 1 and 2, scenario 2 had a reduction (savings) of 230,747 tCO_2eq (27.9 % decrease). This emission reduction was due to the use of a "methane-free" charcoal production process in scenario 2.

The result of scenario 3 had emissions of 752,882 tCO_2eq. This value represents the total amount of greenhouse gases emitted due to demand of charcoal in Kampala, when biomass is sourced sustainably and charcoal is produced using improved production technologies. By decoupling the model and comparing greenhouses gases from charcoal production phases for scenarios 1 and 3, scenario 3 had a reduction (savings) of 801,817 tCO_2eq (96.8 % decrease). GHG emissions of scenario 3 are lower than those of scenarios 1 and 2 because biomass used in the charcoal production process was assumed to be sourced sustainably, thus CO_2 neutral and a methane-free charcoal production process was used in scenario 3. The share of the utilization phase and the transportation phase on the overall emissions increases if production emissions decrease.

The result of scenario 4 shows estimates for greenhouse gases from charcoal production and its utilization for the entire country. By decoupling the model, the charcoal production phase shows the amount of biomass which was/will be used for the production of charcoal in the country for the years 2004, 2011, 2015 and 2020, respectively. This piece of data is quite important because biomass (wood), used for charcoal production in Uganda,

Table 4 Sensitivity analysis for scenario 1

Phase	Emissions	−10 % change	+10 % change	−50 % change	+50 % change
Earth mound charcoal production	Carbon dioxide	−0.0166 %	0.0166 %	−0.0829 %	0.0829 %
Earth mound charcoal production	Methane	−0.0103 %	0.0103 %	−0.0513 %	0.0513 %
Earth mound charcoal production	Nitrous oxides	−0.0004 %	0.0004 %	−0.0020 %	0.0020 %
Charcoal burning (utilization)	Carbon dioxide	−0.0220 %	0.0220 %	−0.1100 %	0.1100 %
Charcoal burning (utilization)	Methane	−0.0012 %	0.0012 %	−0.0061 %	0.0061 %
Charcoal burning (utilization)	Nitrous oxides	−0.0007 %	0.0007 %	−0.0033 %	0.0033 %

Table 5 Sensitivity analysis for scenario 2

Phase	Emissions	−10 % change	+10 % change	−50 % change	+50 % change
PYREG charcoal process (biomass sourced unsustainably)	Carbon dioxide	−0.0188 %	0.0188 %	−0.0940 %	0.0940 %
Charcoal burning (utilization)	Carbon dioxide	−0.0220 %	0.0220 %	−0.1100 %	0.1100 %
Charcoal burning (utilization)	Methane	−0.0012 %	0.0012 %	−0.0061 %	0.0061 %
Charcoal burning (utilization)	Nitrous oxides	−0.0007 %	0.0007 %	−0.0033 %	0.0033 %

presently comes from unsustainable sources, thus, the information would be useful for modelling the deforestation rate in Uganda. With the rate of urbanization in Uganda on the increase and the fact that in Uganda charcoal is mainly used in urban centers (MEMD 2007), it is logical to forecast an increase in charcoal consumption for the country; this will lead to an increase in deforestation, if measures are not taken by the government to ensure that charcoal is produced using sustainably sourced biomass. Alternatively, an introduction of a cheap reliable source of energy for cooking other than charcoal will reverse this anticipated increase in charcoal consumption.

Pennise et al. (2001) estimated annual emissions from charcoal production in Kenya and Brazil for 1996. Table 7 below compares the greenhouse gases emitted from charcoal production gotten from this study with that gotten by Pennise et al. (2001). The results show that greenhouse gas emissions in Uganda are lower than those of Kenya and Brazil, even when compared with recent and projected emission levels in Uganda. This is because of the high charcoal production levels in Kenya and Brazil.

Smith et al. (1999) conducted a study on greenhouse gases from charcoal-making kilns in Thailand. Estimate of annual greenhouse gases from charcoal production for Thailand using CML 2001 characterization factors gave an estimate of 13.4 Mt. Table 7 below shows the comparison with other studies. Looking at the Table 7 critically, we observe that emissions from charcoal production in Thailand are proportionally lower (tCO_2eq emitted per metric tonne of charcoal produced) than Kenyan and Brazilian emissions; this is because a wide range of charcoal kilns with varying degrees of emissions are used in Thailand.

Table 6 Monte Carlo analysis result for scenario 4

Bal row	Scenario 4	Stochastic mean value	Std	10 % percentile	25 % percentile	Median	75 % percentile	90 % percentile
Carbon dioxide	3.32E+06	3.36E+06	10.60 %	2.87E+06	3.05E+06	3.35E+06	3.66E+06	3.85E+06
Nitrous oxide	9.12E+04	9.29E+04	12.50 %	7.67E+04	8.28E+04	9.29E+04	1.03E+05	1.09E+05
Methane	9.89E+05	1.01E+06	13.20 %	8.30E+05	8.98E+05	1.01E+06	1.13E+06	1.20E+06

Table 7 Estimated annual greenhouse gases emitted from charcoal production for Uganda, Kenya, Thailand and Brazil

Charcoal production	Amount of charcoal produced (tonnes)	GHG emitted (tCO_2eq)	GHG emissions (tCO_2eq) per tonne of charcoal produced
Uganda (1996)	657,287[a]	1,946,770	3.0
Uganda (2004)	792,417[a]	2,347,002	3.0
Uganda (2012)	921,494[b]	2,385,535	2.6
Uganda (2015)	970,153[b]	2,511,502	2.6
Uganda (2020)	1,050,365[b]	2,719,155	2.6
Kenya (1996)[c]	2,200,000	6,420,360	2.9
Brazil (1996)[c]	6,400,000	16,433,440	2.6
Thailand (1996)[d]	7,400,000	13,462,080	1.8

[a] Calculated using FAO estimate of charcoal produced for 1996 and 2004, respectively

[b] Calculated using FAO estimates of charcoal produced for 1965–2011 to derive input data for 2012, 2015 and 2020

[c] Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil (Pennise et al. 2001)

[d] Greenhouse gases from small-scale combustion devices in developing countries: charcoal-making kilns in Thailand (Smith et al. 1999)

Chidumayo and Gumbo (2013) estimated greenhouse gases from charcoal production in tropical ecosystems of the world in 2009, using the same emission factors as those used in this study on Uganda. The study result shows that greenhouse gases emitted in Africa was 67.63×10^6 tCO_2eq, while the entire tropical world total was 103.04×10^6 tCO_2eq. Comparing these results with the results from this study shows that greenhouse gases from charcoal production for Kampala (scenario 1) constituted 1.2 and 0.8 % of African and tropical ecosystems of the world greenhouse gas emission, respectively, while greenhouse gases from charcoal production for the entire country (scenario 4) constituted 3.5 and 2.3 % of African and tropical ecosystem of the world greenhouse gases, respectively.

Theoretically, 100 % of charcoal produced in Uganda—792,417 tonnes—can be produced using improved charcoal producing technologies. We observe from Table 1 a switch in charcoal production method from scenarios 1 to 2 and scenarios 1 to 3 resulted in a 27.9 and 96.8 % reduction in GHGs, respectively, for the city of Kampala. Calculating for the country using the same emission factors as the results for Kampala city, will result to emission reduction (savings) of 653, 812 CO_2eq (27.9 %) and 2,271,920 CO_2eq (96.8 %) when switching from scenario 4 to a scenario were biomass is sourced unsustainably and improved charcoal production method is used; to one were biomass is sourced sustainably and improved charcoal production method is used, respectively. However, the non-regulation of the charcoal industry in Uganda; limited knowledge on existing international sources of funding for low-carbon projects and a high poverty rate in the country which makes alternative sources of energy unaffordable, are some constraints hindering the switch to a scenario were charcoal is produced sustainably.

4 Conclusions

This study showcased possible greenhouse gas emission reduction scenarios when charcoal is produced using the earth mound production method; an improved charcoal production process and when biomass feedstock is sourced sustainably/unsustainably. It also showed quantitative estimates of greenhouse gases emitted due to charcoal production and utilization for the entire country—Uganda.

The results of this study, which gave GHG emissions of 3 tCO_2eq emitted per tonne of charcoal produced using earth mound method, can be applied for other countries in Eastern-Africa where similar charcoal production methods are used; this will allow for somewhat better regional estimates of the inventory of greenhouse gas emissions from the production of charcoal. The results of this study were tested to determine its level of quantitative precision using sensitivity analysis and uncertainty analysis; this fell within statistically accepted boundaries.

Scenario 3 has the highest potential for GHG savings. A gradual transition to this scenario would lead to a drop in the country's total GHG emissions. However, completely transiting from scenarios 1 to 3 would be a big task, which is surmountable by enacting appropriate forestry-related laws, establishing vocational training institutes in the field of renewable energy and creating awareness on business opportunities the global transition to low-carbon energy offers for job

creation, especially in developing countries. The results of this study also suggest that the primary use of charcoal for cooking will lead to increases in GHG emissions and increases in deforestation on the long term, if alternative cheap energy-generating technologies for cooking are not developed and deployed to the masses.

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